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Soil CO_2 efflux in Central Amazonia: environmental and methodological effects

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ABSTRACT

Soil respiration plays a significant role in the carbon cycle of Amazonian rainforests. Measurements of soil respiration have only been carried out in few places in the Amazon. This study investigated the effects of the method of ring insertion in the soil as well as of rainfall and spatial distribution on CO_2 emission in the central Amazon region. The ring insertion effect increased the soil emission about 13-20% for sandy and loamy soils during the firsts 4-7 hours, respectively. After rainfall events below 2 mm, the soil respiration did not change, but for rainfall greater than 3 mm, after 2 hours there was a decrease in soil temperature and respiration of about 10-34% for the loamy and sand soils, with emissions returning to normal after around 15-18 hours. The size of the measurement areas and the spatial distribution of soil respiration were better estimated using the Shuttle Radar Topographic Mission (SRTM) data. The Campina reserve is a mosaic of bare soil, stunted heath forest-SHF and tall heath forest-THF. The estimated total average CO_2 emissions from the area was 3.08±0.8 µmol CO_2 m^{-2} s^{-1}. The Cuieiras reserve is another mosaic of plateau, slope, *Campinarana* and riparian forests and the total average emission from the area was 3.82±0.76 µmol CO_2 m^{-2} s^{-1}. We also found that the main control factor of the soil respiration was soil temperature, with 90% explained by regression analysis. Automated soil respiration datasets are a good tool to improve the technique and increase the reliability of measurements to allow a better understanding of all possible factors driven by soil respiration processes.

KEYWORDS: Soil respiration, rainfall, soil temperature.

Efluxo de CO_2 do solo na Amazônia central: efeitos ambiental e metodológico

RESUMO

Respiração do solo possui um importante papel no ciclo do carbono em florestas tropicais Amazônicas. Entretanto poucas medidas de respiração do solo foram feitas. Neste estudo são apontados os efeitos na metodologia de instalação dos anéis no solo, bem como os efeitos da precipitação e a distribuição espacial da emissão de CO_2 na Amazônia central. Os efeitos da inserção de anéis no solo aumentaram de 13 a 20% para o solo arenoso e argiloso, o efeito durou de 4 a 7 horas, respectivamente. Já os efeitos na precipitação, notamos que os eventos abaixo de 2 mm a respiração do solo permaneceu indiferente, mas para precipitação acima de 3 mm, 2 horas depois, houve uma diminuição da temperatura e respiração em 10 a 34% para o solo argilosos e arenosos, retornando a emissão normal após 15 a 18 horas. Para estimar a distribuição espacial da respiração do solo e o tamanho correto das áreas medidas, foram utilizadas as imagens do Shuttle Radar Topographic Mission (SRTM). Considerando que a Reserva de Campina é um mosaico de solo desnudo, floresta alagável de baixa e alta estatura (SHF e THF). A emissão total média de CO_2 para a área foi de 3.08±0.8 µmol CO_2 m^{-2} s^{-1}. Já a Reserva do Cuieiras possui outro mosaico de florestas de platôs, encostas, campinaranas e riparias, sendo a emissão média total desta área foram de 3.82±0.76 µmol CO_2 m^{-2} s^{-1}. Encontramos também que a respiração do solo foi controlada pela temperatura do solo, sendo uma correlação de 90% encontrada pela análise de regressão. Dados obtidos com sistema automático de respiração do solo é uma grande oportunidade de melhoramento da técnica e o aumento da confiança nas medidas em relação aos possíveis fatores que controlam os processos de emissão de CO_2 do solo.

PALAVRAS-CHAVE: Respiração do solo, precipitação, temperatura do solo.

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INTRODUCTION

Changes in terrestrial ecosystems have contributed to atmospheric CO_2 enrichment in both pre-industrial and industrial times. DeFries *et al.* (1999) reported that approximately 40% of the increase in CO_2 since 1800 can be attributed to land–use changes. Increases in atmospheric greenhouse gas concentrations are thought to be responsible for a significant part of the observed increase in average global temperature over the past 50 years (IPCC 2007).

The total global soil carbon pool of 2000–3800 Pg contains about 1550 Pg of organic carbon and 950 Pg of inorganic carbon. This soil C pool is about three times the size of the atmospheric pool (760 Pg) and 4.5 times that of the biotic pool (500–650 Pg) (Gruber *et al.* 2004; Janzen 2004; Lal 2004). According to Schlesinger (1997), 13–17% of the total soil carbon in tropical forests resides in the upper meter of soil and has fast turnover time. Trumbore *et al.* (1996) suggested that the greatest losses of soil carbon due to climate change would be in tropical regions, where their measurements of radiocarbon content indicated the presence of a large pool of soil organic matter with a relatively rapid turnover time. Tropical rainforest fires and deforestation activities in Mato Grosso state, Brazil, have been releasing about 67 Tg C yr^{-1} (DeFries *et al.* 2008).

Soil respiration is the primary process through which CO_2 fixed by land plants is returned to the atmosphere. The soil CO_2 flux is derived from autotrophic and heterotrophic sources. Estimates of future CO_2 changes in the atmosphere depend largely on the feedback of terrestrial ecosystems to climate change, in particular on the balance of C uptake and subsequent loss from ecosystems in a warmer world (Trumbore 2006). Trumbore (2006) also mentioned the discrepancy between the bulk soil respiration measurements conducted in tropical forest environments and process-based models that provide information about the separate contributions from autotrophic and heterotrophic sources.

The availability of such information is a key factor for understanding the response of terrestrial ecosystems to climate change, and it is crucial to understand the effects of variations in biophysical regulators of soil respiration to assess carbon balance in forest ecosystems. However, estimates of soil carbon are highly uncertain (Nakayama 1990; Janssens *et al.* 2000) and difficult to measure because of differences between ecosystems and external drivers such as temperature (Lloyd and Taylor 1994; Davidson *et al.* 1998; Janssens *et al.* 2003), soil moisture (Howard and Howard, 1993), soil texture and chemical properties (Trumbore *et al.* 1995; Liski and Westma 1997), wind speed, leaf litter and root biomass (Reichstein *et al.* 2003; Trumbore 2006) and activity of macro and microfauna (Dantec *et al.* 1999; Giardina and Ryan 2000; Raich *et al.* 2002). Several studies also suggest an influence of seasonal variation in litterfall on soil respiration rates (Reichstein *et al.* 2003; Salimon *et al.* 2004; Valentini *et al.* 2008). However, Metcalfe *et al.* (2007) found a weak correlation between soil efflux related to volumetric soil moisture (R^2=0.44) and non-correlation with temperature in a site in the northwestern Amazon. There was a significant correlation among respiration from soil, litter, roots, and soil organic matter, so the heterotrophic and autotrophic contribution could be estimated.

Various methodologies have been used to study soil respiration in the Amazon region. Coutinho and Lamberti (1971), Martins and Matthes (1978) and Medina *et al.* (1980) measured the soil CO_2 efflux in upland *terra firme* rainforest and short statured *Campina* heath forest by capturing CO_2 in an alkali solution in a closed chamber on the forest floor. Wofsy *et al.* (1988) employed a headspace sampling technique and subsequent field CO_2 analysis of the air with a chromatograph to measure the soil CO_2 efflux. These techniques can be used to estimate long-term emissions, but are less appropriate for assessing variation in short time scales such as those typical for many biological processes. After 1990, soil respiration chambers were connected to infrared gas analyzers (IRGA) to form open- or closed-path and static or dynamic measurement systems (Fan *et al.* 1990; Chambers *et al.* 2004; Metcalfe *et al.* 2007). These modern systems allow assessment of the variation of soil respiration over shorter periods and provide reliable measurements of soil CO_2 efflux. Their operation and particularities have been described in various publications (Livingston and Hutchinson 1995; Dantec *et al.* 1999; Davidson *et al.* 2002; Pumpanen *et al.* 2004). It is often necessary to allow an equilibrium period after ring insertion before starting the soil respiration measurements (Hutchinson and Livingston, 1993; Livingston and Hutchinson, 1995), which was not always done (Chambers *et al.* 2004; Souza 2004). Furthermore, Metcalfe *et al.* (2007), using a rhyzotron to observe deep root growth, showed that in root-free soil it may take up to three months (after rhyzotron installation) before root mass reaches a natural level and that the rate of root growth is approximately linear, whereas root mortality remains negligible.

The present study aimed to assess the influence of ring insertion and precipitation events on instant measurements of soil CO_2 efflux. We also present an overview of soil respiration measurements in various Amazonian forest types and also estimate the total soil CO_2 emission from the Cuieiras and Campina reserves.

MATERIAL AND METHODS

Study sites

The experimental areas were the *Reserva Biológica do Cuieiras* (Cuieiras Reserve), located at 2º 36" 32.67 S, 60º

12" 33.48 W (110 m a.s.l.-above sea level), and the *Reserva de Campina* (Campina Reserve), located at 2º 35" 30.26 S, 60º 01"48.79 W (65 m a.s.l.), both under control of the National Amazon Research Institute (*Instituto Nacional de Pesquisa da Amazônia* - INPA).

The Cuieiras Reserve covers 22.7 hectares and is located about 70 km north of Manaus-AM, Brazil (Chambers *et al.* 2004; de Araújo *et al.* 2002). The landscape consists of unconsolidated sedimentary layers which are dissected by rivers and streams, creating a pattern of rather flat plateaus (90-130 m a.s.l.) and swampy valleys (45–55 m a.s.l.), separated by moderately steep slopes (15-30º) (Waterloo *et al.,* 2006) (see Figure 1a, for additional site details of the transect). The vegetation is a mosaic of evergreen forest with a canopy height of about 35 – 40 m, with emergent trees over 45 m tall, varying to ecotone *Campinarana* and valley or riparian forest, according to the slope. Such forests cover about 5-6% of Amazonia and depend on variations in soils, nutrients and drainage conditions (Luizão *et al.* 2007). The recent development of the Height Above the Nearest Drainage (HAND) descriptor based on the Shuttle Radar Topographic Mission (SRTM) elevation data allows the classification of terrain according to water table depth and topography (Rennó *et al.* 2008). Analyses of the Igarape Asu catchment (Cuieiras Reserve area) indicated that valley forest environments (riparian and *Campinarana*) cover 43% of the area, whereas slope and plateau (*terra firme*) forests occupy 26% and 31%, respectively. The Leaf Area index (LAI) measurements were performed with an LI–2000 apparatus (LI–COR, Nebraska, USA) during the wet and dry season in April, July–September 2007 and in the same periods of 2008. The measurement design consisted of two grids, one in the *Campinarana* and another in the riparian forest of Cuieiras and two others in the Campina Reserve. Both grids consisted of three parallel lines with 15 m spacing between them and 100 m in length. The measurements were made at one-meter intervals and all values were averaged for the wet and dry season. The LAI for the plateau forest was 6.1 (Marques-Filho *et al.,* 2005) and the LAI for the *Campinarana* forest was 5.02±0.62 and for riparian forest was 5.82±0.58.

Cuieiras Reserve has these main vegetation types: the riparian area consists of Arecaceae, Caesalpiniaceae, Dichapetalaceae and Burseraceae (I. L. Amaral, unpublished) families, followed by the *Campinarana,* which contains Caesalpiniaceae, Euphorbiaceae and Sapotaceae. In turn, the slope forest contains Lecythidaceae, Sapotaceae, Chrysobalanaceae and Burseraceae and the plateau (*terra firme*) contains Lecythidaceae, Sapotaceae, Fabaceae and Euphorbiaceae (Oliveira and Amaral, 2004; Oliveira and Amaral, 2005). All these areas have their own singular characteristics and some *Campinarana* species occur in both Campina and dense *terra firme* forests (Proctor 1999; Luizão *et al.* 2007). The transition from *Campinarana* to lowland evergreen rainforest is marked by the sudden appearance of palms in the understory and a drastic reduction of the root mat (Luizão 1996), which is determined by the soil properties and different species.

Soils on the plateau are clayey Oxisols, whereas the slopes are dominated by Ultisols. Valley soils generally consist of strongly leached quartz sands, classified as Spodosols and Gleys, with low water and nutrient retention (Brinkmann 1985; Chauvel *et al.* 1987; Waterloo *et al.* 2006), high phenolic content and acidity (Proctor 1999).

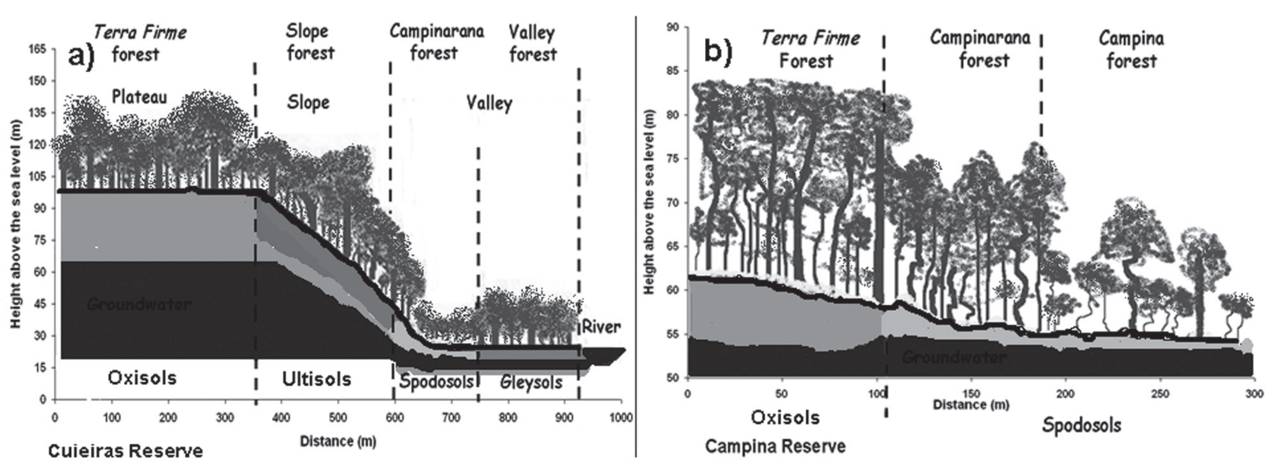

Figure 1 - Typical topographic transect from tropical rainforest (Central Amazonia), where soil respiration was measured in different forest types. a) Cuieira Reserve, which has a steep inclination forest and is composed of a mosaic of riparian, Campinarana, slope and plateau forests with their respective soil types; b) Campina Reserve, which presents the transition from plateau forest via Campinarana to Campina forest, containing also differences in soil types and properties.

The Campina Reserve is located 60 km north of Manaus. The reserve has approximately 900 ha, of which 6.5 ha is stunted heath forest (SHF) and tall heath forest (THF). The SHF area (2.6 ha) is formed by a mosaic of shrub islands surrounded by white bare sandy soil and 3.9 ha of the THF area together with the rest of the reserve consists of lowland evergreen rainforest. The canopy height is about 4–7 m for SHF, 10-18 m for THF and 25–35 m for *terra firme* forest (Luizão 1996) (see Figure 1b for additional site transect details). Using the Shuttle Radar Topographic Mission (SRTM) elevation data, we separated an area of 500 x 500 m and analyzed the georeferenced points. The image vegetation contrast was used to indicate the percentage of the vegetation area, which was 73% of the THF, 15% of the SHF, while 11% of the area was bare soil. The *terra firme* forest was not included in the analysis because it is located outside the selected area. The LAI were measured with an LI-2000 apparatus (LI–COR, Nebraska, USA) during April, July–September of 2007 and also in the same periods in 2008. The same method was used in the Campina Reserve as in the Cuieiras, but with only one grid in the SHF and another in THF. The SHF forest LAI was 2.43±1.28 and for the THF it was 3.85±0.96.

The main characteristics of the Campina Reserve are the structure and scleromorphic physiognomy that distinguish heath forests from the other regional forests types. They have extremely nutrient-poor white sandy soils (spodosols) with low species richness, dominated by one or more species and unusual physiognomy: shorter stature, many branched and tortuous trees and bushes with scleromorphic leaves and considerable load of vascular epiphytes (Orchidaceae, Bromeliaceae, Araceae, Ericaceae) and lichens (Anderson 1981; Richards 1996). The shrub and tree species are *Ouratea spruceana* (Ochnaceae), *Pagamea duckei* (Rubiaceae), *Pradosia schomburgkiana* (Sapotaceae), *Adina heterophylla* (Caesalpiniaceae) (Anderson 1981; Luizão 1996). There were also species which belong only to these areas due to adaptation to each soil, micro climate and specific environmental characteristics. For example, the Campina Reserve shares only 3.2% of species with *terra Firme* forest and 17% with the *Campinarana* forest (Oliveira and Amaral 2004).

The spatial and temporal climate in the central part of the Amazon region does not change much. The annual average temperature is 26.7 °C with relative humidity of about 80%. The annual rainfall (1966-1992) reported about 75 km SE from the Campina Reserve (Ducke Rainforest Reserve) amounts to 2442 mm, with a standard deviation of 306 mm (Waterloo *et al.* 2006). The dry season occurs from June to November. The Campina Reserve is drier than the Cuieiras Reserve, because the forest is more open, contains a small canopy and is formed by small islands of bushes, allowing more wind and heat to enter the understory.

Soil measurements

Soil respiration was measured randomly using an LI–8100 automated soil CO_2 flux system (LI–COR, Nebraska, USA) attached to an LI-8100-101 long-term chamber (20 cm in diameter). Measurements were also performed using another automated system developed by Alterra Institute, The Netherlands. This system consists of two chambers measuring 25 cm high and 30 cm in diameter made of polyethylene coupled to a CO_2 an LI–840 analyzer (LI–COR, Nebraska, USA). Both systems have output in µmol CO_2 m^{-2} s^{-1}.

The measurement methods were based on dynamic chambers (Norman *et al.,* 1992) and measurements were taken once every 30 minutes during 24 hours. Following Hutchinson and Livingston (1993), the systems were installed at 2 cm depth into clayey soils and 3 cm into sandy soils.

Measurements using the LI–8100 system were made in one place chosen randomly during a week and then the system was moved to another place inside of the measurement area or to a different location inside of the Cuieiras Reserve or the Campina Reserve (Figure 1). The measurements in the Campina area were carried out between 20 July and 11 October 2007. The measurements in the Cuieiras Reserve were performed as follows: on 8 February 2007 and between 13 November and 13 December 2007 in the riparian area; between 20 November 2006 and 31 May 2007 in the *Campinarana* area; between 28 June and 12 July and between 12 and 22 December 2006 in the slope area; and between 3 August and 6 November 2006 and again between 21 and 26 February 2008 in the plateau area.

Measurements were made with another soil respiration system (Alterra system) in the *Campinarana* forest of the Cuieiras Reserve. This system consists of a chamber with a lid closed by means of an electric motor with pulley and rope. The measurements are taken when the lid closes automatically at programmed measurement intervals. Inside the chamber the system has a fan to mix the air (Micronel, D341T, Vista, USA). The air enters the chamber through polyethylene tubing placed at the base and leaves through a similar tube below the chamber lid. There is also a pressure balancing tube which equalizes the pressure between the chamber and the outside air. The lid is sealed with two hollow neoprene bands to prevent any external contamination.

The LI–8100 system measurements were performed one week after the ring installation in order to prevent any error in the results that could be attributed to the soil disturbance. On some occasions spare polyvinyl chloride (PVC) rings were not available to be installed before the random measurements. Soil ring insertion produced outliers, which were removed by statistical analyses for the number of standard deviations from the mean. However, to identify the ring insertion effects we used the first data set compared with the next three days of measurements and the outliers were calculated by the increase compared to the average results.

Effect of rainfall events was also checked, using the data to assume the influence obtained 24 hours before and 24 hours after the rainfall events. This data were compared for different amounts of rain and for all sites measured.

For the spatial distribution variation of soil CO_2 respiration, we used the Shuttle Radar Topographic Mission (SRTM) images. The types of forests area were delimited together with local measurements of soil CO_2 respiration, where the total average emission weight for each reserve was estimated.

Near the soil chambers, soil moisture and temperature sensors were installed at 10 cm depth and 5 and 10 cm depths, respectively. Both sensors measured at the same frequency as the LI-8100 and the Alterra systems.

Statistical analysis

The Kruskal–Wallis test and one–way analysis of variance (ANOVA) by ranks were applied. This is a nonparametric method for testing the equality of population medians among groups of soil respiration from all different measured areas. Because it is a nonparametric method, the test does not assume a normal population. However, it does require an identically shaped and scaled distribution for each group, except for any difference in medians. This test was used because another statistical test was performed in relation to the mean and the possible outlier data from rain events or some high or low efflux emission measurements that could reduce the statistical significance of the analysis.

Regression analysis was performed to examine the relationship between soil respiration and soil moisture and to ensure that the residuals were equally distributed about the regression line with constant variance (homoscedasticity) where the significant effects were determined ($p<0.05$). All statistical analyses were performed using the Matlab software (version 7.0, The MathWorks, Inc.).

RESULTS AND DISCUSSION

Ring insertion effect

The variability of soil CO_2 efflux requires an accurate measurement method and the measurements need to be taken in many different places (Sotta *et al.* 2004). The final results can be underestimated if the methodology is not appropriate. This study found that ring insertion caused an increase of about 13–20% in the mean value of soil CO_2 efflux for the first 7 hours (Figure 2).

Keller *et al.* (2000) reported that ring installation might damage the soil by breaking the micro and macro soil chambers, including roots, and can release high concentrations of CO_2, NO, N_2O and CH_4. However, soil has some mechanisms that can minimize these emission effects and reduce the time scale of the artificial influence, (e.g., photosynthesis, transpiration, precipitation, physiological processes and decomposition rates). Metcalfe *et al.* (2008) reported a high root increase in a short period. In particular, fine roots, which can grow more than 2 cm per day, are an important indicator that soil can recover quickly (about 7 hours) in tropical surface layers (2 cm depth).

Nevertheless, it takes some time until the natural soil CO_2 emissions are established again, depending on the soil and forest type. Across the surveyed sites, these artificial mechanical factors caused extra emissions and the majority of emission variation persisted between 4 to 7 h after the ring installation. The loamy soils (n=5, 3 in the plateau and 2 in the slope forest, $p<0.05$) showed an increase of 15–20%. The sandy soil (n=6, 4 in the Campina and 2 in riparian Cuieiras area, $p<0.05$) also showed an increase of 13–18%.

These variations in CO_2 emission are not important if the measurements are performed for long periods. This can be achieved by using an automatic system for 24 hours. We noted that a maximum of 7 hours after the insertion, the effluxes stabilized to normal emission rates for all soils measured at the study sites. On other hand, when the system was used randomly and the measurement is taken punctually after ring insertion, the overestimation can add a few tonnes to the yearly carbon estimates (Chambers *et al.* 2004; Souza 2004). In general, this waiting period is doubtful (Davidson *et al.* 2002) and it is necessary first to check how long the ring insertion affect will influence the mean results.

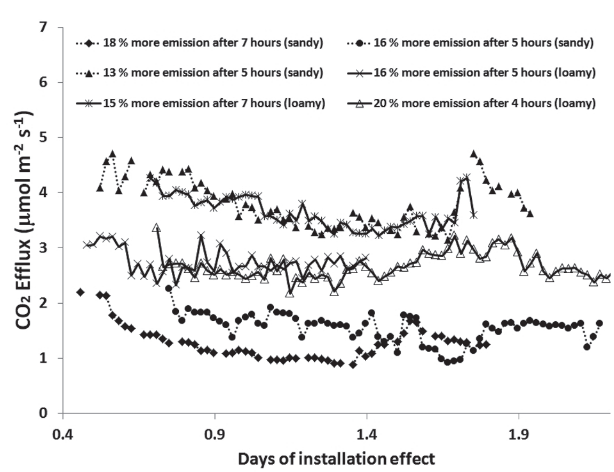

Figure 2 - Effect on the soil CO_2 efflux emission after the ring installation (soil insertion) for all different site measurements in the Cuieiras and Campina reserves. The time line is in fractional days after the ring installation following CO_2 measurements.

Rainfall effect

There was a considerable variation in the soil CO_2 efflux related to precipitation events. The efflux for all soils and forest types also behaved differently.

Nevertheless, there were no changes for the plateau and slope areas (clayey soils, rainfall below 2 mm, n=4), but there was an increase of less than 10% in the first hour. Then the soil CO_2 efflux returned to normal. Sotta *et al.* (2004) reported that soil respiration has some effect after rain events less than 2 mm. In this study, we also found an increase in the soil CO_2 efflux related to rainfall, but not for precipitation below 2 mm (F. B. Zanchi, in prepare, interception data from 2006–2007). We noticed that this amount of rainfall generally did not reach the forest ground, and therefore it could not cause any change in the soil respiration, temperature and moisture in the top layer.

When the rainfall was between 3 to 8 mm (n=3), we noted an increase in the emission of about 10 to 18% for the next 2 hours. After this period, the efflux dropped by 15% compared to the normal efflux and returned to normal after 17 hours. During this period the soil temperature changed slightly.

With rain events greater than 8 mm (Figure 3), we noticed two large changes in the soil emission. The total of the first event was about 12 mm and the soil moisture in the top 10 cm increased from 0.30 to 0.39 $m^3\ m^{-3}$ in 2 hours, and there was a small spike in the soil CO_2 in the same period after the rainfall event. After 2 hours, the soil moisture started to decrease and the soil respiration decreased due to the groundwater percolation through the soil pores. The soil CO_2 emissions only returned to a normal diurnal cycle after 18 hours (about 22% less), caused by the rainfall effect. Likewise, after 22 mm of rainfall, we noticed that the emission was suppressed immediately after the event, by about 27%, followed by a decrease in soil temperature (Figure 3).

On the other hand, we found different variations for sandy soils. In the *Campinarana* forest (Cuieiras Reserve, Figure 4), a rainfall event bigger than 3 mm did not change the CO_2 emission. Between 3 to 10 mm rainfall (n=11), the respiration increased quickly by 34% during 2 hours and returned to normal after 4 hours. Rainfall greater than 15 mm (n=2) caused a quick decrease in CO_2 efflux, an effect that lasted for 5 hours at low rates, while the soil moisture also changed quickly from 0.1 to 0.15 $m^3\ m^{-3}$ during the same period. The soil temperature showed a slight decrease in this period (Figure 4).

For the same sandy soils but in a different forest composition (Campina Reserve), the THF and SHF soil respiration behaved similarly, showing little change compared to the mean emission (<10% for 15 hours). Figures 5 and 6 show a slight decrease followed by a large spike for 2 hours after the rain event, which decreased the amplitude of the soil CO_2 diurnal cycle. The soil temperature also decreased and there was a quick increase for a few hours in the soil moisture, perhaps because of the sandy soil and small CO_2 production in this type of forest.

Two hours after big rainfall events, soil CO_2 emission decreased by 10 to 27%. Similar results were found by Matteucci *et al.* (2000), Sotta *et al.* (2004) and Savage *et al.* (2009), all of whom found this rainfall influence, but for other soil types.

In addition, there were abrupt changes in the soil temperature when the rainfall event was bigger than 10 mm (Figures 3 to 6). These soil CO_2 efflux increases were noticed in all 7 analyzed events. Perhaps the reason of this increase is more

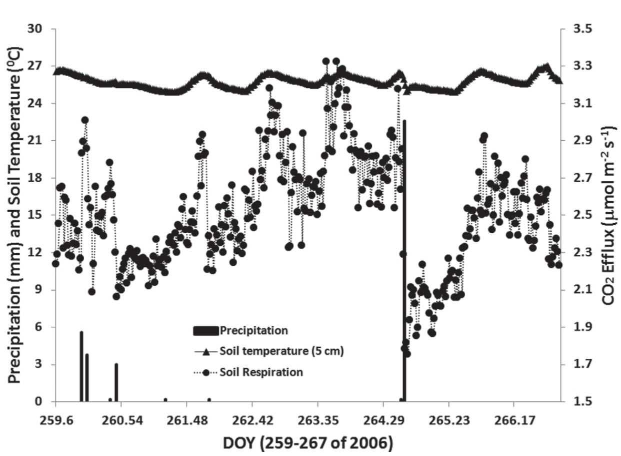

Figure 3 - Change in the soil CO_2 efflux emission for the loamy soil of the plateau forest from Cuieiras Reserve caused by precipitation. The effect decreased the emission by 25% (n=4) for 18h after the rainfall event compared with the previous emission. In days of year (DOY) from 259-267 of 2006.

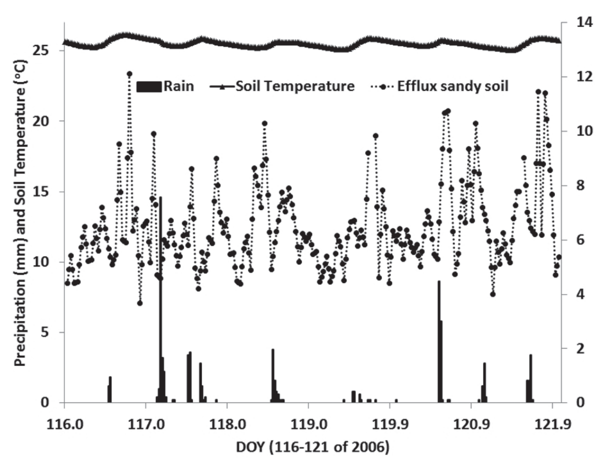

Figure 4 - Effect of rainfall events on soil CO_2 efflux emission for the sandy soil of *Campiranara* forest from Cuieiras Reserve. The effect decreased the emission by 7% (n=6) in relation to the previous emission around 7h after the rainfall events. In days of year (DOY) from 116-121 of 2006.

a physical effect than an effect of groundwater percolation derived from 2 mm rainfall, because the air pressure dropped around 3 to 5 mbar just before and during the rainfall events. We could not find any other strong relation for small precipitation to ascertain which factor affected the soil evasion other than atmospheric pressure. And the amount of rain was not big enough to provoke such high spikes and influence the soil evasion. Some authors (e.g., Hutchinson and Livingston 1993; Lund *et al.* 1999; Davidson *et al.* 2002) stated that slight changes in atmospheric pressure can influence soil CO_2 emissions. Maybe this was the reason small rainfall amounts caused a change in the soil CO_2 emissions in this study.

However, it is still unclear if the precipitation was the main factor influencing the soil CO_2 emission due to high/low soil moisture content, but we can also hypothesize that the bacterial decomposition of organic matter and the water filling of soil pores may trigger an increase in CO_2 emission, as mentioned by Linn and Doran (1984). Moreover, atmospheric pressure can have an important influence on the CO_2 emissions (Hutchinson and Livingston 1993).

Spatial distribution

There was a significant variation between sites in the recorded CO_2 efflux variables (Table 1). For 23 different Amazonian sites, the mean value was 4.2±1.8 µmol CO_2 and the coefficient was greater than 42% among all the sites. Table 1 and Figure 7 both show an example from two small catchments, where we found that the soil CO_2 variation

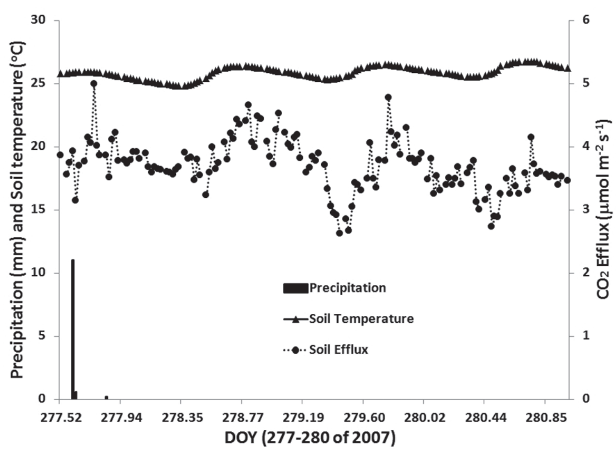

Figure 5 - Rainfall influence on the soil CO_2 efflux emission. The rainfall did not change the mean CO_2 emission for the sandy soil of THF forest in Campina Reserve, but the efflux had some effect about 2h after the rainfall event, with an abrupt increase before returning to the regular emission level again. In days of year (DOY) from 277-280 of 2007.

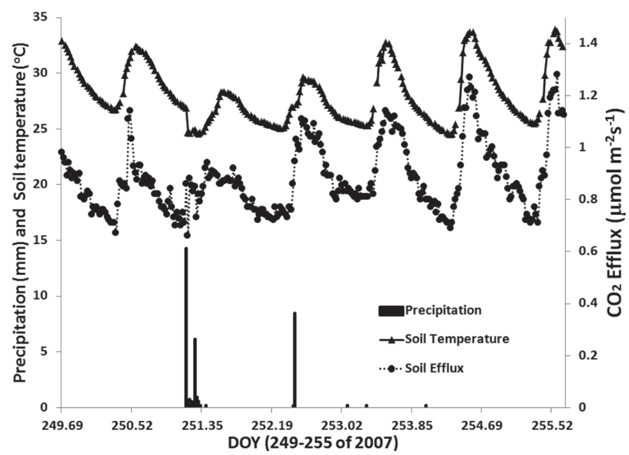

Figure 6 - Effect of rainfall events on the soil CO_2 efflux emission. The precipitation did not change the mean CO_2 emission, but the emission had a slight effect on the soil respiration, followed by soil temperature decrease for the SHF forest from Campina Reserve. In days of year (DOY) from 249-255 of 2007.

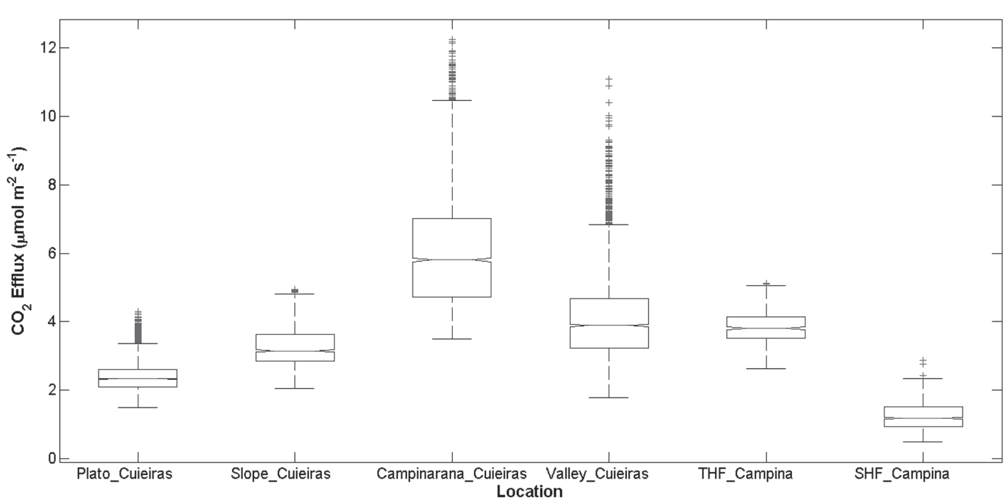

Figure 7 - Topographical gradients from the rainforest in the central Amazonia along which CO_2 were measured in different locations of the Cuieiras and the Campina reserves. The boxplot describes the minimum sample, lower quartile, median, upper quartile and maximum emission sampled from each location.

Table 1 - Soil CO_2 efflux measurements using different methods at Amazonian sites. Soil CO_2 efflux in μmol CO_2 m^{-2} s^{-1} and soil temperature in °C. (Sotta et al., 2004, adaptation).

Author	Season	Location	Vegetation	Soil Temperature (°C) (depth)	CO_2 Efflux (μmol CO_2 m^{-2} s^{-1})	Methodology
Coutinho & Lamberti (1971)	Dry season (Aug–Sep)	Barcelos, AM, Brazil	Closed Rainforest	25–28 soil temperature	2.8	Aqueous solution 0.5N KOH
Martins & Matthes (1978)	Dry season (Jul)	Manaus, AM, Brazil	Campinarana, Campina	Not stated	1.4 ± 0.5	Chemical system – aqueous solution 0.5N KOH
Medina *et al.* (1980)	2 years long	San Carlos do Rio Negro, Venezuela	Laterite Forest	22–27 forest floor	3.1 ± 0.5	Chemical system – aqueous solution 0.5N KOH
Wofsy *et al.* (1988)	Dry season (Jul-Aug)	Reserva Ducke, Manaus, AM, Brazil	Closed Rainforest	Not stated	4.5	Chromatography – closed static system
Fan *et al.* (1990)	Wet season (Apr–May)	Reserva Ducke, Manaus, AM, Brazil	Closed Rainforest	Not stated	5.9	IRGA – closed dynamic system
Kepler *et al.* (1990)	Not stated	Fucada, Manaus, AM, Brazil	Forest, Pasture and burned forest	24	6,5± 0.6	IRGA – closed Static system
Meir *et al.* (1996)	Wet-to-dry season (May-Jun)	Reserva do Jarú, RO, Brazil	Open Rainforest	22.9 soil temperature	5.5 ± 1.6	IRGA – closed dynamic system
Trumbore *et al*, (1995)		Paragominas, PA, Brazil,	Open Rainforest		6,1	IRGA – closed dynamic system
Davidson *et al.* (2000)	Year long	Fazenda Vitória, Paragominas, PA, Brazil	Open Rainforest	22–24 (10 cm)	5.3	IRGA – closed dynamic system
Chambers *et al.* (2004)	Year long	Manaus, AM, Brazil	Open Rainforest (plateau)	Not stated	3.8	IRGA – closed dynamic system
Souza (2004)	Year long	Manaus, AM	Open Rainforest (plateau)	24.5 (5 cm)	5,76	IRGA – closed dynamic system
Sotta *et al.* (2004)	End of wet season	Manaus, AM, Brazil	Closed Rainforest (plateau)	25.6 (5 cm)	6.4 ± 0.25	IRGA – open dynamic System
Salimon *et al.* (2004)	Wet and dry season	Rio Branco, Acre, Brazil	Closed Rainforest (plateau) and pasture	23.8 ± 0.8 (5 cm)	4.73	IRGA – closed dynamic system
Valentini *et al.* (2008)	Year long	Sinop, Mato Grosso, Brazil	Closed Rainforest (plateau)	24 (5 cm)	7.6 ± 0.5	IRGA – closed dynamic system
Goulden *et al.* (2004)	Year long	Tapajos	Closed Rainforest (plateau)	26 (5 cm)	3.38	IRGA – closed Static system
Present study	Wet and dry season	Cuieiras Reserve, Manaus, AM, Brazil	Closed Rainforest (plateau)	25.7± 0.6 (5 cm)	2.4±0.4	IRGA – closed dynamic system
			Slope Forest	25.3± 0.3 (5 cm)	3.2± 0.5	
			Campinarana	25.6±0.5 (5 cm)	6.0±1.6	
			Valley Forest	25.8±0.6 (5 cm)	4.1±1.2	
	Wet and dry season	Campina Reserve, Manaus, AM, Brazil	Campina THF	25.8±0.4 (5 cm)	3.8±0.4	
			Campina THF	26.7±2.57 (5 cm)	1.2±0.3	
			Campina Bare soil	28.4±2.22 (5 cm)	0.99±0.14	

between soil types and vegetation was high. Inside the Campina reserve, which contains bare soil along with SHF and THF areas, the variations were 0.99±0.14, 1.2±0.3 and 3.8±0.2 respectively. In the Cuieiras Reserve, where a transect from the upper to lower area of around 900 m in length is present (Figure 1), we also found the highest differences between the vegetation and the soil types. Consequently, the soil emission rates showed large differences, which changed in relation to plateau, slope, *Campinarana* and riparian forests and where the soils vary from clayey to sandy. In these areas, the soil respiration levels were 2.4±0.4, 3.2±0.5, 6.0±1.6 and 4.1±1.2 μmol CO_2 m^{-2} s^{-1}, respectively.

The *Campinarana* and the THF sites inside each reserve had the highest emissions. Both microenviromental areas have similar vegetation and soil type. The main characteristics of these sites differ from another place of this study, by having a thick root matter and litter layer in the first 5 to 10 cm of soil. The emissions were higher here than at all the other sites.

To quantify the total CO_2 efflux from the Campina and Cuieiras reserves, we calculate the weighted average according to the size of each vegetation type. Assuming that the vegetation of the reserves grows in each soil type, we described the areas using the SRTM images. The images provided a suitable mesh for each forest size from the Campina Reserve, where THF=73%, SHF=15% and bare soil=11% of the total area. The weighted average of the whole Campina Reserve was found using the equation R_{tCP} = (3.83*0.73) + (1.2*0.15) + (0.99*0.11), and the total Campina emission was 3.08±0.8 μmol CO_2 m^{-2} s^{-1}. The Cuieiras Reserve's weighted average was estimated using the same method, plateau = 31%, slope = 26% and riverine (*Campinarana* and riparian forest) = 43% of the area. The equation was R_{tCU} (2.4*0.31) + (3.2*0.29) + (5*0.43), with a total emission of 3.82±0.76 μmol CO_2 m^{-2} s^{-1} for the entire area of Cuieiras Reserve.

An important improvement compared to previous studies of the Cuieiras Reserve (Chambers *et al.* 2004; Sotta *et al.* 2004; Souza 2004) and Campina Reserve (Martins and Matthes 1978) was the fact we managed to quantify the CO_2 emissions in relation to the vegetation and soil types.

The spatial variation results for all the measured sites (Figure 7, F =18479 d.f.=5, $p=0$) showed a strong indication that the spatial variations for testing equality of population medians among groups were not the same, with a difference prevailing between all the sites measured.

To find the relation of soil temperature or the main driven factor on the soil respiration, we selected from the dataset only periods without rainfall. An Exponential model adjusted for a daily cycle of soil respiration with soil temperature dependence at 5 cm. We noted a hysteresis on both variables. Soil respiration answer faster to the physical parameters compared to the soil temperature. To obtain a better fit curve, was necessary to shift–back around 3 hours the soil temperature related to soil respiration, which could predict the time hysteresis (Gaumont-Guay *et al.* 2006, Pavelka *et al.* 2007, Pingintha *et al.* 2010). The simple model turns to, $Rs=0.0598*e^{0.1435*Temp}$, with the R^2=0.9, $p<0.05$. Afterwards the model was applied for the whole soil temperature dataset, showing a similar pattern for both and a better fit curve.

Sotta *et al.* (2004) also found that rainfall events explained 75% of the correlation between soil CO_2 and soil temperature decreases. We assumed that the main driver of the soil CO_2 efflux for all the sites was soil temperature. While rainfall had an influence in both decreases, the main factor influencing emission was soil temperature.

CONCLUSIONS

To quantify the total CO_2 emission, all information about the underlying controls upon respiration from different soil and vegetation were important (e.g. soil disturbs and rainfall intensity). On the other hand, by not applying the correct methodology, this study indicated an overestimate of 20 % in the total soil CO_2 emission.

To minimize the soil disturbance and waiting time after ring installation before starting measurement, it is essential to know the soil type and vegetation characteristics. In general, the loamy soil was more sensitive to mechanical disturbance and took longer to return the natural emission level than sandy soil.

Rainfall events showed different patterns. The loamy soils were more stable than the sandy soils. For moderate rainfall events (8 mm), the increase in CO_2 efflux from sandy soil was 50% faster than for the loamy soils, and decrease after 2 to 3 hours, which did not happened in the loamy soils.

On the other hand, we found that the main factor influencing the soil respiration was soil temperature, because the soil respiration followed the same pattern as the temperature, while rainfall only caused a brief disturbance in the soil respiration. Rainfall seems to contribute only by creating favorable conditions for a quick decrease in temperature and consequently the respiration followed the physical effect of soil water percolation. We also noticed that it was difficult to account for the rainfall effects in the simple model estimation. This has some implications for future modeling studies over space and time, because rainfall causes overestimation of the total model emission and it is not easy to include the CO_2 emission spikes in the models.

Finally, the quantification of the total increase in CO_2 emission was better estimated using the total weighted average area compared to the local measurements from previous estimation studies. Thus, for better estimation of soil CO_2 effluxes, or to model a region and vegetation type, it is necessary to find the main influencing factors to decrease the uncertainties about the final carbon release measurements.

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